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THE CONSTRUCTION AND INSTALLATION OF THERMOCOUPLES FOR BIOLOGICAL RESEARCH[1]

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INTRODUCTION

The thermocouple, when connected with a potentiometer, has several advantages over other instruments used to determine temperature changes in biological material. In the first place any temperature within its range may be determined instantly. Moreover, it is an improvement over the mercurial, spirit, or gas thermometer in that its small size permits measurement of temperatures in localized areas of living or dead tissue. Within limits, the distance from the thermocouple to the potentiometer is immaterial and a whole battery of thermocouples can be coupled with one potentiometer through a centrally located switchboard. Temperatures may, therefore, be recorded in rapid succession. Finally, thermocouples may be left in position indefinitely where corrosion does not take place.

In attempting to use this apparatus for biological research the writer discovered that many temperature readings were inaccurate. Later these inaccuracies were found to be due largely to incorrect mounting of the thermocouples. Further investigation revealed that many others who made temperature measurements in similar work with this equipment had used it without taking adequate precautions to prevent the same difficulty (*1*, *2*, *3*, *5*).[3][4]

Portable potentiometer indicators have found extensive use in industrial research and manufacturing. The measurement of the temperature of furnaces, of flowing liquids, and of rooms located at considerable distances from each other are among the multitude of ways in which they are employed. But under such conditions it is not difficult to set up thermocouples to measure temperatures correctly since the volume of material or the space held at a specific degree or

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[3] Italic numbers in parentheses refer to Literature Cited, p. 341.

[4] CALAHAN, C. L. THE PORTABLE POTENTIOMETER THERMOCOUPLE THERMOELECTRIC INDICATOR METHOD FOR RAPIDLY DETERMINING SMALL TEMPERATURE CHANGES IN LIMITED AREAS. N. H. Univ. Dept. Hort. 18 pp., illus. 1942. [Processed.]

range is comparatively large. In biological experiments it is frequently desirable to measure the temperature of limited areas, or differences in the temperature of tissues which are but a fraction of an inch apart.

Information dealing with the technique of using the portable potentiometer and installing thermocouples for this work is very scattered, incomplete, and contradictory. The material that follows was secured as a result of efforts to overcome difficulties arising in the construction of thermocouples and in mounting them to obtain accurate temperature readings in biological research experiments.

It is not intended to discuss in this paper the construction and operation of the potentiometer any more than is necessary. These problems have already been solved by the manufacturers of such instruments, and explained by authors of many textbooks of physics and chemistry (*6*, *7*.).[5] It is necessary, however, to consider briefly the construction of the apparatus with which this work was done.

THE POTENTIOMETER

The most practical instrument found to measure temperatures of biological materials, so far, has proved to be a potentiometer calibrated directly in temperature units.

The potentiometer has been in general use since about 1912. In its simplest form it is well described by Duff (*4*). The one used by the writer, which is called a null balance instrument, measures thermocouple electromotive force by comparing it with the standardized voltage drop across a portion of a slide-wire, and uses a sensitive galvanometer to detect any unbalance. It consists essentially of a resistance wire of uniform and constant resistance throughout its length, in series with a battery and a current-adjusting rheostat. The voltage drop across the wire, or any part of it, is proportional to the current flow. It is necessary to use a current flow of constant value in this circuit as a standard of comparison. In order to check this constant flow it is necessary, at frequent intervals, to compare the voltage drop due to the battery current flowing across a calculated portion of slide-wire with the e. m. f. of a circuit carrying the opposing voltage of a standard cell (e. m. f.=1.0190 volts). The galvanometer is used to detect any current which would flow if the potentials were not equal, and a rheostat in the battery circuit is adjusted until such equality is obtained. Any effects of variations of temperature on the e. m. f. of the battery circuit, with which the e. m. f. of the thermocouple is to be compared, can be eliminated completely before the latter is switched into the circuit in place of the standard cell.

Since no current flows from the thermocouple when the measuring instrument is balanced, the accuracy of measurement is usually independent of the length or diameter of the thermocouple leads, when they are properly installed. Therefore, when measuring temperatures of a group of thermocouples, it is not necessary to have all leads the same length, nor to "balance" the shorter leads with additional

[5] LEEDS & NORTHRUP COMPANY. MICROMAX TERMOCOUPLE PYROMETERS FOR MEASUREMENT AND CONTROL. Leeds & Northrup Co. Cat. N-33A, 57 pp., illus. Philadelphia. 1942.

resistance. Certain limitations concerning length and size of leads will be discussed later.

Calibration of this potentiometer depends upon stable and fixed resistance coils and slide-wires rather than on delicate deflection meters. The sensitive galvanometer is used as a null balance detector only and is not calibrated.[6]

CONSTRUCTION OF THERMOCOUPLES

The terms "thermocouple," "couple," and "junction" are used interchangeably in this paper. A thermocouple, as ordinarily described in physics, consists of two wires of unlike material fused or soldered together to make two junctions. The copper wire is then cut in two at the center to serve as leads to the measuring instrument. If the two junctions are at different temperatures, there is a voltage between the two lead-wires and this is measured. The measurements are standardized by placing one of the junctions in melting ice at a constant temperature.

The type of thermocouple, or, strictly speaking, the portion of thermocouple employed in the following investigation is made up of two wires each of a different metal, welded, fused, or soldered together at one end. An electromotive force, or electrical pressure, is developed at the point of junction of the wires and is proportional to the temperature difference between this point, the so-called "hot" junction, and the reference or "cold" junctions, located in this case in the instrument to which the free ends of the wires (lead-wires) extend. At this point it should be understood that it is possible, and necessary, to solder the hot junction and short leads of No. 30 or finer wire, to larger lead-wires of the same metals, and extend these to the instrument if the latter is more than 15 feet away. The potentiometer employed is also equipped with an automatic reference junction compensator which eliminates the need for the ice bath described above, a decided convenience for tests run in the field and over a long period of time.

To be most useful in obtaining internal plant temperature, thermocouples must of necessity be as small in diameter as it is practical to make them so that there will be the least possible injury to the tissue in which they are inserted. Number 30 copper-constantan enameled wire was selected as about the smallest that could be used conveniently in this work. Number 38 and possibly finer can be obtained,[7] but these would require such sensitive galvanometers that they could be used only under carefully controlled laboratory conditions and are too easily broken to be useful for temperature studies under field conditions extending over a long period.

Each potentiometer is calibrated for thermocouples made of specific materials.

Several batteries of thermocouples were made for these experiments.

[6] The instrument referred to was a manually operated Leeds & Northrup portable potentiometer indicator with automatic reference junction compensator. It is calibrated −40° to 120° F., for use with copper-constantan thermocouples (1938 calibration).

[7] BAKER & CO., INC. FINE WIRES. 15 pp. New York, San Francisco, and Chicago. [No date.]

The copper and the constantan lead-wires from each thermocouple in a battery were the same length, but those in different batteries ranged in length from 3 feet up to 115 feet. Short wires were cut in pairs and each pair was wrapped on a spool. Couples with long lead-wires were marked by attaching identically numbered tags at both ends, but a whole battery of these thermocouples and leads was wrapped on one spool. When unwound it was, in effect, a cable. This practice removed the necessity of keeping the small, easily tangled lead-wires separated from each other throughout their whole length, and greatly simplified installation.

In constructing a thermocouple the enamel was first scraped off one end of each of two wires. Fine emery cloth is an excellent material with which to remove enamel. These cleaned ends were twisted tightly together for several turns, and were then fused by holding them in the flame of a medium hot gas burner with the twisted ends turned upward at an angle of from 60° to 70° above the horizontal position.

Copper has a melting point of 1,083° C. and will, therefore, melt before the constantan, an alloy of nickel and copper, which has a melting point of 1,290° C. At its melting point the copper fuses around the constantan. This point can best be observed by watching for it through a large lens. A reading glass is satisfactory. Wires must be removed from the flame the instant fusion takes place, and before a droplet of copper forms, or before the wire melts apart. Small droplets do not appear to interfere with the accuracy of readings, but do interfere with the insertion of the thermocouple into plant material, and could, if they were large enough, result in excessive thermal conduction because of their large heat capacity. Any piece of constantan which protrudes beyond the tip of the fused junction can be cut off easily with a sharp knife if the projection is first laid on a solid surface.

Satisfactory thermocouples can also be made by cleaning the ends of the wires, twisting them together for a short distance, and then soldering the twisted portion to prevent corrosion and hold it firm. Thermocouples used in these experiments were either fused, or fused and soldered, and they gave equally good results. A concentrated zinc chloride flux, used in the process of soldering, was very effective. The fused junctions or twisted wires were first dipped into the zinc chloride flux, then inserted into solder heated to a temperature considerably above the melting point, and immediately withdrawn. An excellent junction is produced by this method, but any zinc chloride remaining on it should be rinsed off in water to prevent corrosion. A more durable and equally efficient couple can be made by fusing the ends of the wires and soldering them together up to one-eighth of an inch from the junction. However, any additional material placed around or near the junction requires extra space, makes installation difficult, and introduces additional error due to thermal conduction.

If a sufficient length of lead-wires, including the junction, can be embedded at the same depth in the object to be measured, it will not be necessary to fuse the extreme tips of wires for junctions to be used in measuring the temperature of objects, as will be shown later, since this practice prevents thermal conduction toward or away from the junction. In measuring the temperatures of thin or small

objects it would, of course, be preferable to make the junction occupy as little space as possible, which can be done by fusing the ends of the wires by means of an electric arc.

INSTALLATION OF THERMOCOUPLES

WORK OF OTHER INVESTIGATORS

Thermocouples have frequently been used to measure the internal temperature of plants. Clum (*1*) describes apparatus for and methods of measuring leaf temperatures. He used No. 36 copper-constantan wire in his experiments. The thermocouples were fused with an electric current and were insulated with "Radiolac." Lead-wires at an undesignated distance from the junctions were also protected by running them through cotton sleeving. Junctions were inserted into the mesophyll of the leaf through a small hole in the lower epidermis and held in place with a small wire clamp slipped over the edge of the leaf and over the thermocouple wires a short distance from the junction. By this method only a few millimeters of junction and adjoining lead-wires would be embedded in plant tissue.

Wallace and Clum (*11*), in later work on leaf temperatures, used thermopiles consisting of clusters of five thermocouples of No. 38 copper-constantan wire. These were mounted on a wire clip within a wire frame 6 mm. square which was pressed against the lower surface of the leaf when the clip was closed on the leaf. This would seem to be an excellent method of obtaining the temperature at the lower surface of leaves, but would not necessarily determine the internal temperature of a leaf at any given instant, since thermal conduction could affect the temperature of the couple on the leaf but not that of the couple suspended in air. However, it is obvious that the No. 38 wire used would introduce far less error than No. 30 wire.

Eaton and Belden (*5*) also used No. 36 copper-constantan wire in their measurements. Their thermocouple wires were enclosed in "semiflexible tubing" from which the junctions protruded about 1 inch. The upper surface of a leaf was folded against the junction with a pair of cork-tipped tongs and the reading on the galvanometer taken immediately. The results were in terms of "the departures of the leaf temperatures from the temperature of the air," which were obtained from a shaded thermocouple (*5, p. 35*).

Curtis (*2, 3*) used No. 30 copper-constantan thermocouples which he "threaded" through the leaves. All except about 1 cm. of junction and lead-wires was insulated. In this work the junctions of the thermocouples and short lengths of adjacent lead-wires were in contact with the lower surface of the leaf. In wire of this size the thermal conduction factor exerts a great influence on temperature readings, as will be shown. Insulating lead-wires to within 1 cm. of the junction, on the basis of the following work, is of questionable value, especially in recording temperatures that can change as rapidly as they do in leaves. Insulating material would absorb heat during a rise in temperature at the junction, and would permit it to be conducted back to the junction as the latter point becomes cooler. This would definitely tend to straighten the temperature curve.

Patton and Feagan (*8*) devised an ingenious method of measuring

the fall in temperature of a liquid flowing through a tube. Thermocouple junctions were soldered in the ends of slots machined in the wall of a metal tube parallel to its length. These junctions were located very near the inner wall of the tube. Lead-wires were then run through a smaller tube laid in the machined slot. This smaller tube was also soldered in place and the solder ground down at the surface to restore the original outer curvature of the pipe. By this method the thermocouple junction and about 3 inches of lead-wires were exposed to the same temperature, and false readings due to thermal conductivity away from the junctions were eliminated.

OBJECTIVES

Because of their sensitivity, thermocouples have long been of outstanding value in measuring plant temperatures. The writer wished to use them both in trunks and branches of trees and at various distances above and below ground. However, suspicion arose as to possible variability in readings due to thermal conduction along the lead-wires. Many readings were taken in comparison with those of a mercury medical thermometer placed under the human tongue. The readings averaged from 1° to 1½° lower for the thermocouples made of No. 30 copper-constantan wire, but when the lead-wires adjacent to the junction were bent into the form of a compact S the error was eliminated.

A series of experiments was carried out to determine whether there was thermal conduction of heat away from the thermocouple junction along the lead-wires to a colder point some distance away, or vice versa, and whether such conduction would affect temperature readings when copper-constantan thermocoulpes of No. 30 gage were used. Studies also were made to find a method of inserting thermocouples in plant tissue in such a way as to avoid incorrect readings, or at least to reduce the inaccuracies to a minimum.

METHOD OF PROCEDURE

Equipment was set up to determine what effect would be produced by conduction of heat toward or away from the thermocouple junction. For this work several thermocouples of No. 30 copper and constantan wire were prepared by welding in a gas flame. Some of these were dipped in solder and others left as welded to test the effect of soldering All gave identical temperature readings when checked against a standard couple. The comparison was made by suspending the couples to a depth of 6 inches in water that had stood for 48 hours in a room at nearly constant temperature. A standardized thermometer was used as a further check.

Thermocouples with lead-wires 115 feet long gave as accurate readings on the potentiometer previously described as thermocouples with 4-foot lead-wires at temperatures of O° F. or above. However, the galvanometer needle was less sensitive to thermocouples with the long leads during the measurement of subzero temperatures. This was especially important since the nearest peach trees in which couples were to be inserted were located 100 feet from a room in which the instrument was to be placed in order to operate it in cold weather. Larger lead-wires of copper and constantan were not available. But

when low temperatures are to be measured at a distance of more than 15 feet from the instrument it would be preferable to make thermocouples and short lead-wires of No. 30 copper-constantan wires and solder them to No. 16 gage insulated leads of the same metals to eliminate high resistance in the galvanometer circuit. One group of tests for thermal conductivity was carried out with 4-foot couples, the other with 9-foot couples. The results are recorded in the data that follows.

TESTS SHOWING CONDUCTION ALONG LEAD-WIRES IN AIR TO A JUNCTION SUSPENDED IN WATER

In the first set of experiments a thermocouple was suspended one-half inch deep in a gallon jar of water that had stood in a room of nearly constant temperature for 48 hours (fig. 1). The temperature of the water both before and after the experiment was 77.75° F. By means of a measuring stick mounted besides the apparatus it was possible to indicate the exact point above the water at which the lead-wires were grasped by the fingers of the operator. This method was sufficiently accurate to show the desired results since the chief concern was whether or not thermal conduction influenced temperature readings during these first experiments rather than the exact amount of variation. Obviously there is opportunity for variation in the temperature of the fingers, particularly where short lengths of wire are grasped, but this would minimize rather than amplify the results

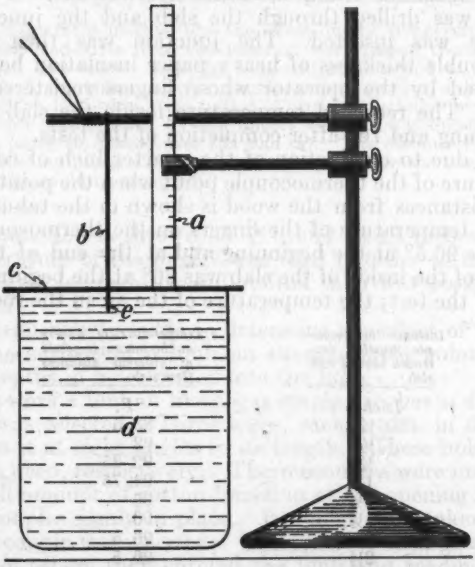

FIGURE 1.—Apparatus used to test for thermal conductivity along lead-wires to a thermocouple junction suspended in water: (*a*) Ruler; *b*, thermocouple lead-wires that were grasped at various distances above *c*; *c*, insulating paper; *d*, water; *e*, thermocouple junction.

under the conditions of the experiment that follows. The tabulation given below shows the results of the experiment to determine the conductivity of heat from fingers, through metal in air and water, to a thermocouple junction.

Distance above water at which wires were grasped by fingers	*Temperature reading after 20 seconds*
Inches	° *F.*
3	77. 75
2	77. 75
1	77. 75
½	78. 50
¼	81. 25

This tabulation indicates that heat from the fingers was conducted along the No. 30 wires and was not dissipated into the air or water and thus prevented from reaching junctions located less than 1 inch from its source. The thermal differential or the difference between the temperature of the fingers (96.5° F.) and of the water (77.75°) was only 18.75° F. at the beginning of this experiment.

EVIDENCE OF THERMAL CONDUCTION IN EXPERIMENTS WITH LIVE WOOD OF SUGAR MAPLE

Trials were carried out with a slab one-quarter inch thick cut from a young, dormant sugar maple tree on a winter day when the temperature was well above freezing. The wood was very moist. Sap flowed freely from the stump after the tree was cut. A hole 1 mm. in diameter was drilled through the slab and the junction of the thermocouple was inserted. The junction was then pushed on through a double thickness of heavy paper insulation beyond which it was grapsed by the operator whose fingers registered 96.50° F. (See fig. 2). The recorded temperature inside the slab was 66° F. at the beginning and 70° after completion of the tests.

The effect due to conduction of the quarter inch of cold wood on the temperature of the thermocouple point when the point was moved to various distances from the wood is shown in the tabulation given below. The temperature of the fingers on the thermocouple outside the wood was 96.5° at the beginning and at the end of the test; the temperature of the inside of the slab was 66° at the beginning and 70° at the end of the test; the temperature of the air in the room was 79°.

Distance thermocouple function protruded beyond cold slab	*Temperature of fingers on thermocouple points at different distances from slab*
Inches	° *F.*
¼	85. 5
½	92
¾	92. 25
1	94. 75
1¼	95
1½	96
2	96. 5
2½	96. 5

With a difference of 30.5° F. between the temperature in the slab and that of the fingers it is apparent from these figures that at a distance of ¼ inch the temperature reading of the object at the ther-

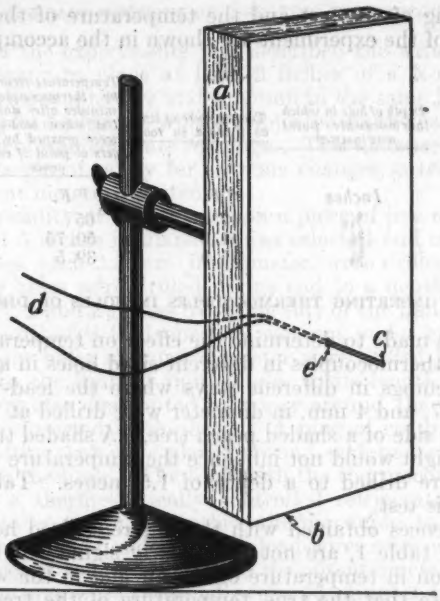

FIGURE 2.—Apparatus used to test the effect on the temperature at a thermocouple when lead-wires from the junction were passed through green maple wood which was colder than the temperature recorded at the junction: *a*, Maple slab; *b*, insulating paper; *c*, thermacouple junction; *d*, lead-wires; *e*, hole through which lead-wires were pulled to various distances beyond slab. The thermocouple was grasped by the fingers when it was one-fourth inch from insulation paper (*b*) placed over the slab (a). The distance from the junction to the insulation paper was increased 2 inches before the true temperature of the fingertips could be recorded.

mocouple junction is thrown off 11°, and at 1½ inches it is off 0.5°. The temperature of the fingers was used in order to measure results with a greater temperature differential than was possible in the air of the room.

An experiment was made to determine the effect of high temperature at the surface of a limb on thermocouple points inserted to different depths in holes drilled into the limb.

For this work a limb ot live sugar maple 4 inches in diameter and 3 feet long was selected. Three holes, each 1 mm. in diameter, were drilled into it at right angles to its length. These holes were 1/16, 3/8, and 5/8 inch deep, respectively. Thermocouples were inserted in them and a small amount of cotton forced in at the opening in the bark to hold the couples firmly in place. Readings were taken immediately after each couple was inserted. The operator then grasped the wires at the point where they entered the limb and readings were taken again. All temperatures were recorded within an interval of 3 minutes, beginning with the thermocouple which was 1/16 of an inch deep. The temperature of the room in which the limb stood was 79° F. at

the beginning of the test and the temperature of the fingers, 96.5°. The results of the experiment are shown in the accompanying tabulation.

Depth of hole in which thermocouple point was inserted	*Temperature of limb as it stood in room*	*Temperature recorded by thermocouple 3 minutes after start of test when lead-wires were grasped by fingers at point of emergence*
Inches	*° F.*	*° F.*
1/16	47.5	65
1/4	41.5	50.75
1/2	36.0	39.5

EFFECT OF INSERTING THERMOCOUPLES IN HOLES OF DIFFERENT SIZES

A test was made to determine the effect on temperature recordings of inserting thermocouples in different-sized holes in a tree and plugging the openings in different ways where the lead-wires emerged. Holes 1.5, 1.7, and 4 mm. in diameter were drilled at the same level on the north side of a shaded peach tree. A shaded tree was selected so that sunlight would not influence the temperature of the couples. All holes were drilled to a depth of 1.5 inches. Table 1 gives the results of this test.

The differences obtained with the different sized holes and plugs, as shown by table 1, are not particularly significant because of the small variation in temperature of the air and in the wood, but they might indicate that the true temperature of the tree at 1½ inches deep was not being measured accurately and that the junctions as they were inserted were affected by the temperature of the air. Differences would probably have been greater at higher temperatures or during more rapid changes in temperature. Discrepancies are probably due in part to the curvature of the tree and differences in the structure of the wood.

TABLE 1.—*Temperatures recorded when thermocouples were inserted in holes of different size in peach tree and held in place by different methods*

Date and time of day	Temperature in holes of different sizes with couples held in place as indicated				
	1.5 mm.; cotton plug	1.7 mm.; cotton plug	4 mm.; cotton plug	1.7 mm.; cotton plug grafting wax	Temperature of air
	°F.	°F.	°F.	°F.	°F.
Dec. 18:					
6:00 p. m.	13.75	13.75	14.0	13.75	12.0
7:15 p. m.	10.5	10.5	10.5	10.0	8.75
9:00 p. m.	7.25	8.0	8.0	7.5	5.5
Dec. 19:					
7:00 a. m.	−3.5	−3.0	−3.0	−3.0	−2.5
12:00 m.	4.0	4.0	4.0	4.0	5.0
1:45 p. m.	5.0	5.0	5.0	5.0	4.5
6:00 p. m.	−2.0	−1.5	−1.5	−1.5	−4.0
11:00 p. m.	−11.0	−11.0	−11.5	−11.5	−12.0
Dec. 20:					
8:30 a. m.	−15.5	−15.5	−15.25	−15.5	−14.25
10:15 a. m.	−10.0	−10.25	−10.0	−10.5	−7.0
12:45 p. m.	−1.0	−1.25	−1.5	−1.5	4.25
5:30 p. m.	4.25	4.25	4.25	4.25	3.75

A COMPARISON OF METHODS OF INSERTING THERMOCOUPLES

As a result of the experiments just described the writer concluded that it is necessary to place at least 3 inches of a No. 30 copper-constantan thermocouple wire and junction in the same level of plant tissue, or at a place where it will be subjected to the same temperature, in order to obtain accurate readings. This distance was selected to provide a margin of safety for extreme changes in temperature in tissue of different moisture content.

To test the validity of this conclusion a piece of live apple limb 16 inches long and 5 inches in diameter was selected and cut off. Two sets of four holes, each 2.5 mm. in diameter, were drilled in it. The first set of four holes were drilled in one end to a depth of 3 inches. These were ¼, ½, 1 and 2 inches from the side of the limb and parallel to it, but so distributed that one hole was not under another. The second set of four holes of equal diameter were drilled ¼, ½, 1, and 2 inches deep into the limb at right angles to its length and surface. These holes were also distributed part way around the limb. Thermocouples were inserted in the holes. A plug of cotton and a light covering of grafting wax were placed around each pair of wires where it emerged from the limb. The limb with the thermocouples inserted was placed in a thermostatically controlled refrigerator capable of being cooled to −40° F. Another thermocouple to indicate air temperature was placed beside it. The lead-wires were passed through a hole in the wall of the refrigerator to the potentiometer located outside. Temperatures were recorded every 15 minutes from the time the compressor was started until it was shut off and the inside of the chamber had again reached the temperature of the room. During the time the temperature was rising, the door fasteners of the refrigerator were released slightly to allow warm air to enter and cold air to drain out; however, the air inside was circulated sufficiently by a large fan so that it was of uniform temperature at any given moment. After the couples had been removed the limb was cut to check the position of points at the base of the 3-inch holes. The results with thermocouples set at ¼ inch in each of the two tests are illustrated in fig. 3.

The results of this experiment indicate that during rapid changes in temperature at higher levels, thermocouples set at shallow depths, with but ¼ inch of wire embedded in the tree, may read from 3° to 9° lower or higher than temperatures registered on a couple 3 inches of which is embedded at the same depth. When temperatures are changing at a lower rate the difference between readings of thermocouples in the tree and those in air become more nearly the same regardless of how the instruments are inserted in the tree, since there is less conduction of heat toward or away from these junctions. The conditions indicated in figure 3 for the period between 5:30 and 8:00 p. m. are comparable to those sometimes occurring in an orchard between 9:00 a. m. and 1:00 p. m. on a bright, sunshiny day in midwinter. Any thermocouple set in a hole ¼ inch deep drilled at right angles to the bark, as indicated in figure 3, would not register correctly because of the great amount of heat conducted along the wire to the junction. When 3 inches of the wires are embedded at ¼ inch depth, hot or cold air striking them where they enter the tree would

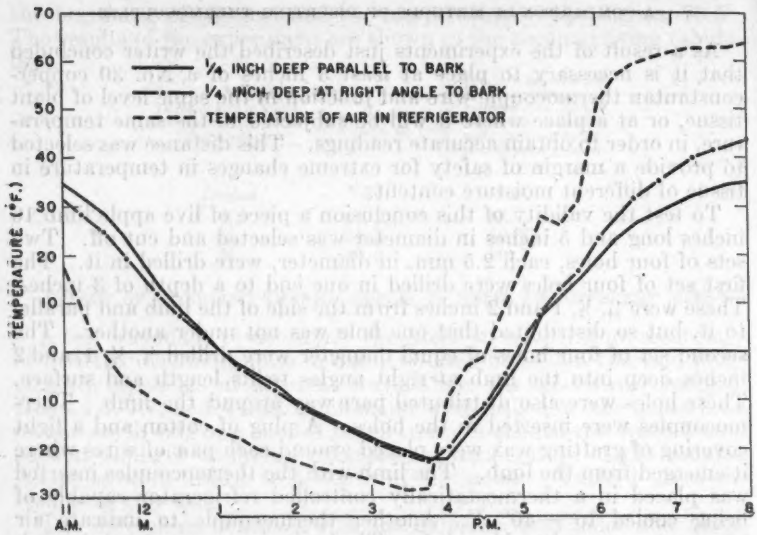

FIGURE 3.—Effect of thermal conduction on the temperature at a thermocouple junction installed ¼ inch deep at a right angle to the surface of an apple limb 5 inches in diameter as compared with its effect at another junction, also set ¼ inch deep, but inserted parallel to the surface of the limb for a distance of 3 inches.

be dissipated before reaching the junction, resulting in a more nearly perfect record of conditions at that location. The accuracy of this statement is indicated by figure 4, which shows the results obtained by setting the couples about 2 inches deep. When the limb was cut, the point of couple No. 1 proved to be 1⅞ inches deep, which accounts for the slight discrepancy in the readings. However, at this depth the readings of both thermocouples follow the same curve with but little variation, indicating that little influence, if any, resulted from conduction of heat along the wires toward, or away from, these points.

Since it would be extremely difficult to insert a thermocouple and 3 inches of adjoining lead-wires parallel to the length of a tree trunk at a depth much greater than the cambium, the following method was devised for measuring temperatures deeper in the trunk. One-fourth-inch bamboo reed was cut into lengths about 2 inches longer than the radius of the tree to be measured, and a small steel wire was pushed through them to open the nodes. A hole was drilled in the trunk into which the reed was inserted for a trial fitting. The depth to which the reed extended was carefully measured, after which it was withdrawn and shallow, close spiral notches were cut in its outside wall at distances which represented the depth at which thermocouples were to be placed. The thermocouples and lead-wires were then inserted in the reed and were allowed to protrude from it at the desired point for a distance of 3 inches. Between three and four wraps around the ¼-inch reed will, even when slightly separated, occupy little

space, but will absorb the 3 inches of lead-wires and will therefore reduce to a minimum the amount of thermal conduction along the lead-wires toward or away from the junction. The whole unit was then dipped in shellac, and when it dried the wires were held firmly in place for inserting in the tree. If the unit has more than one thermocouple on it, lead-wires should be carefully labeled. A small amount of grafting wax was applied where lead-wires emerged from the tree.

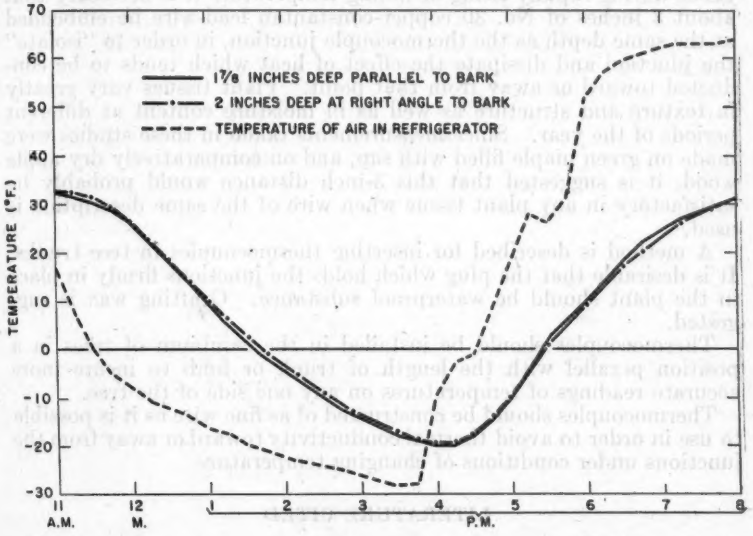

FIGURE 4.—Effect of thermal conduction on the temperature of a thermocouple when junctions were installed as indicated in figure 3 but at a depth of about 2 inches. The temperatures recorded in figures 3 and 4 were taken on the same apple limb at the same time.

In the event bamboo reeds are not available, small, straight branches can be cut from young, live wood not over ¼-inch in diameter. When the bark is peeled off these they can be split lengthwise and the pith removed, after which they can be used like the bamboo reeds described above.

An excellent time of year to place thermocouples in the cambium layers of trees to study winter temperatures is when the bark slips in August. A hard steel wire sharpened on one end and pushed vertically along the trunk into the cambium can be forced along the latter very easily at that time of year. If inserted immediately after the wire is withdrawn, a thermocouple can, without difficulty, be pushed into position. A small amount of grafting wax can be brushed on the hole where the wires emerge, and they will soon become firmly established.

SUMMARY AND CONCLUSIONS

The potentiometer-thermocouple method of measuring the internal temperature of plants is accurate if the thermocouples are properly installed. Within working limitations the size of the hole in which a couple is placed is not as important as other factors of installation, but from the standpoint of injury to plants the smallest hole in which a junction can be inserted is best.

In order to obtain an accurate reading of temperature in live wood tissue during rapidly rising or falling temperature it is necessary that about 3 inches of No. 30 copper-constantan lead-wire be embedded at the same depth as the thermocouple junction, in order to "isolate" the junction and dissipate the effect of heat which tends to be conducted toward or away from that point. Plant tissues vary greatly in texture and structure as well as in moisture content at different periods of the year. Since measurements taken in these studies were made on green maple filled with sap, and on comparatively dry apple wood, it is suggested that this 3-inch distance would probably be satisfactory in any plant tissue when wire of the same description is used.

A method is described for inserting thermocouples in tree trunks. It is desirable that the plug which holds the junctions firmly in place in the plant should be waterproof substance. Grafting wax is suggested.

Thermocouples should be installed in the cambium of trees in a position parallel with the length of trunk or limb to insure more accurate readings of temperatures on any one side of the tree.

Thermocouples should be constructed of as fine wire as it is possible to use in order to avoid thermal conductivity toward or away from the junctions under conditions of changing temperature.

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